THE JOURNAL OF INDUSTRIAL HYGIENE

VOLUME XI NOVEMBER, 1929 NUMBER 9

THE EVALUATION OF 5 AND 7 PER CENT. CARBON DIOXIDE MIXTURES AS RESPIRATORY STIMULANTS*

EMERY HELLER, M.D.[1]

WALTER KILLICHES, M.D.[1]

AND

CECIL K. DRINKER, M.D.

From the Department of Physiology, Harvard School of Public Health, Boston, Mass.

INTRODUCTION

SINCE the publication of the final report (1) of the 1921 Commission on Resuscitation from Carbon Monoxide Asphyxia, there has been an ever-increasing use of the method of treatment devised by Henderson and Haggard prior to the appointment of the Commission and further developed by them as members of this body. The method consists in causing persons asphyxiated by carbon monoxide to breathe a mixture of 5 per cent. carbon dioxide and 95 per cent. oxygen. This mixture is carried in a portable inhalator of convenient type and has proved an entirely safe therapeutic agent to place in the hands of nonmedical rescue crews.

It has been necessary for one of the authors (C. K. D.) to watch the use of this gas mixture in the treatment of many cases of carbon monoxide poisoning, the experience including both mild and severe gassing. There can be no doubt as to the efficacy of the method. At the same time, it seems possible that the original recommendation of 5 per cent. carbon dioxide was too low. At the final meeting of the Commission on Resuscitation, certain members with experience in carbon dioxide inhalation felt that higher concentrations might cause headache and that in the early use of a new

*Received for publication Aug. 5, 1929.

[1]Fellows of the International Health Board of the Rockefeller Foundation.

therapeutic procedure every care should be exercised to avoid the slightest untoward effect.

No careful measurements exist which show the efficacy of a single carbon dioxide concentration, let us say 5 per cent., in stimulating breathing as carbon monoxide saturation of the blood progresses.

When a high concentration of carbon monoxide is breathed, one may obtain a very pure type of asphyxia in relatively few minutes. Under these circumstances there is little shift in the acid-base equilibrium in the blood. The respiratory center experiences oxygen lack abruptly, and changes in the response to carbon dioxide stimulation express this effect without the complicating factors which accompany slower poisoning. In this latter case, carbon monoxide is inhaled

TABLE 1.—NORMAL MINUTE-VOLUME OF TWENTY-TWO YOUNG MEN AND INCREASED VOLUMES DUE TO BREATHING 5 PER CENT. CARBON DIOXIDE IN AIR

SUBJECT	HEIGHT	WEIGHT	AGE	AVERAGE MINUTE-VOLUME		INCREASE IN MINUTE-VOLUME ON BREATHING 5 PER CENT. CARBON DIOXIDE IN AIR	
				Breathing Air	Breathing 5 Per Cent. Carbon Dioxide in Air	Average	Maximum
	cm.	*kg.*	*yrs.*	*liters*	*liters*	*per cent.*	*per cent.*
1. P. D.	193.0	73.3	35	7.6	19.0	150.0	188.1
2. C. K. D.	188.0	72.2	41	7.0	20.4	191.4	252.8
3. W. T. G.	187.0	75.0	22	9.9	28.3	185.8	300.0
4. G. D. K.	187.0	77.5	25	6.7	14.6	117.9	164.1
5. W. C. S.	186.5	85.8	21	8.3	18.2	119.2	189.1
6. T. W. C.	185.6	70.5	23	8.5	26.0	205.8	282.3
7. J. R. S.	184.0	78.1	24	6.25	22.8	264.8	391.2
8. W. S. G.	184.0	68.4	24	6.0	15.2	153.3	195.0
9. G. H. S.	182.5	75.0	22	7.9	23.2	193.6	249.3
10. F. S. D.	181.0	72.2	29	9.7	21.8	124.7	169.0
11. L. A. S.	181.0	61.9	42	7.5	16.7	122.6	170.0
12. S. M. D.	180.5	67.4	23	6.5	18.3	181.5	226.1
13. S. W.	180.0	68.3	29	10.3	30.9	200.0	257.2
14. L. R. P.	179.5	78.2	22	6.8	21.7	219.1	326.1
15. W. B. P.	176.5	75.8	23	7.8	28.6	266.6	343.5
16. J. K. H.	176.5	75.0	22	8.03	23.5	192.6	246.2
17. H. W.	174.5	79.0	30	7.2	16.0	122.2	180.5
18. W. K.	171.0	76.9	29	7.3	25.0	242.4	345.2
19. F. S. W.	170.5	73.0	21	7.0	16.3	132.8	182.8
20. J. E.	170.0	78.0	22	9.0	20.3	125.5	206.8
21. T. H.	170.0	60.0	27	8.0	14.9	86.2	152.5
22. C. P. Y.	168.0	59.4	33	7.5	15.9	112.0	144.0

in low concentration over a long time. There is a period of hyperpnea of varying length and a resulting alkalosis due essentially to breathing out carbon dioxide. When this situation is reached, the patient's breathing is at first bad, not necessarily because oxygen want may have reduced the functional activity of the cells of the respiratory center, but because the normal stimulating value of carbonic acid within the cells of the center is not easily reached. A patient so affected is eminently in need of carbon dioxide and is best treated by giving carbon dioxide inhalations, but the immediate effect of the carbon dioxide will not give so great an increase of respiration as in the normal individual. Similarly, in acutely developing and extremely severe carbon monoxide anoxemia, the immediate effect of carbon dioxide will not be to give so great a respiratory response as one can obtain under normal conditions.

In both acute and chronic poisoning, we are confronted with a situation in which the threshold of the respiratory center for stimulation is in effect raised. The natural remedy would be to increase the carbon dioxide content of the inhalation mixture, but before this was done the authors have felt it necessary to get a better conception of the stimulating value of clinically useful carbon dioxide mixtures for normal persons.

Experimental Study

The subjects were all young adult men and women, either medical students or members of the laboratory staff. They inhaled the gas mixtures in the morning or in the afternoon—frequently at both times. No effort

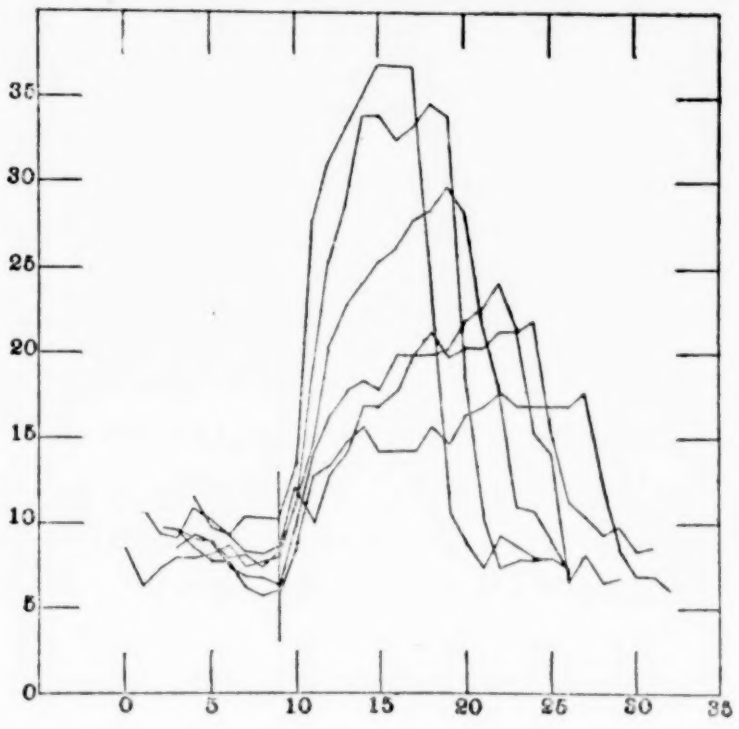

Fig. 1.—Response of six young men to inhalation of 5 per cent. carbon dioxide in air. Ordinates, minute-volume in liters; abscissas, time in minutes.

was made to have the subjects in a basal condition. All were in thoroughly good health during the periods of observation and thus give a reliable indication of individual response to carbon dioxide inhalation.

Gas mixtures were made from commercial carbon dioxide; oxygen was used instead of air in a few control experiments, but, as might be expected, had no effect upon the result. The air plus carbon dioxide mixtures were contained in a counterbalanced 300-liter spirometer, being carefully stirred to secure uniformity of composition and analyzed before each observation.

Wide-bored vacuum cleaner tubes led from this spirometer to an ordinary rubber mouthpiece. An expiration valve, close to the subject's mouth, allowed the exhaled mixture to pass out into the room air. A second, 100-liter spirometer filled with room air was connected by a T-valve to the first line. On entering the laboratory the subject lay upon a bed for a

brief period; he then adjusted the mouthpiece of the apparatus and breathed through the tubing but not from the air containing spirometer, this being possible by means of a by-passing valve near the spirometer. When the subject was entirely comfortable, and without his knowledge, he was thrown into connection with the air containing spirometer and his minute-volume was read until it became uniform. The operator then shifted the breathing to the large spirometer containing carbon dioxide. The subject was almost immediately conscious of the change—both as a result of increased breathing and also from the slight but distinctive taste of the gas. The carbon dioxide-air mixture was breathed until the spirometer was practically exhausted, minute-volumes being read through the entire period. The length of the period of

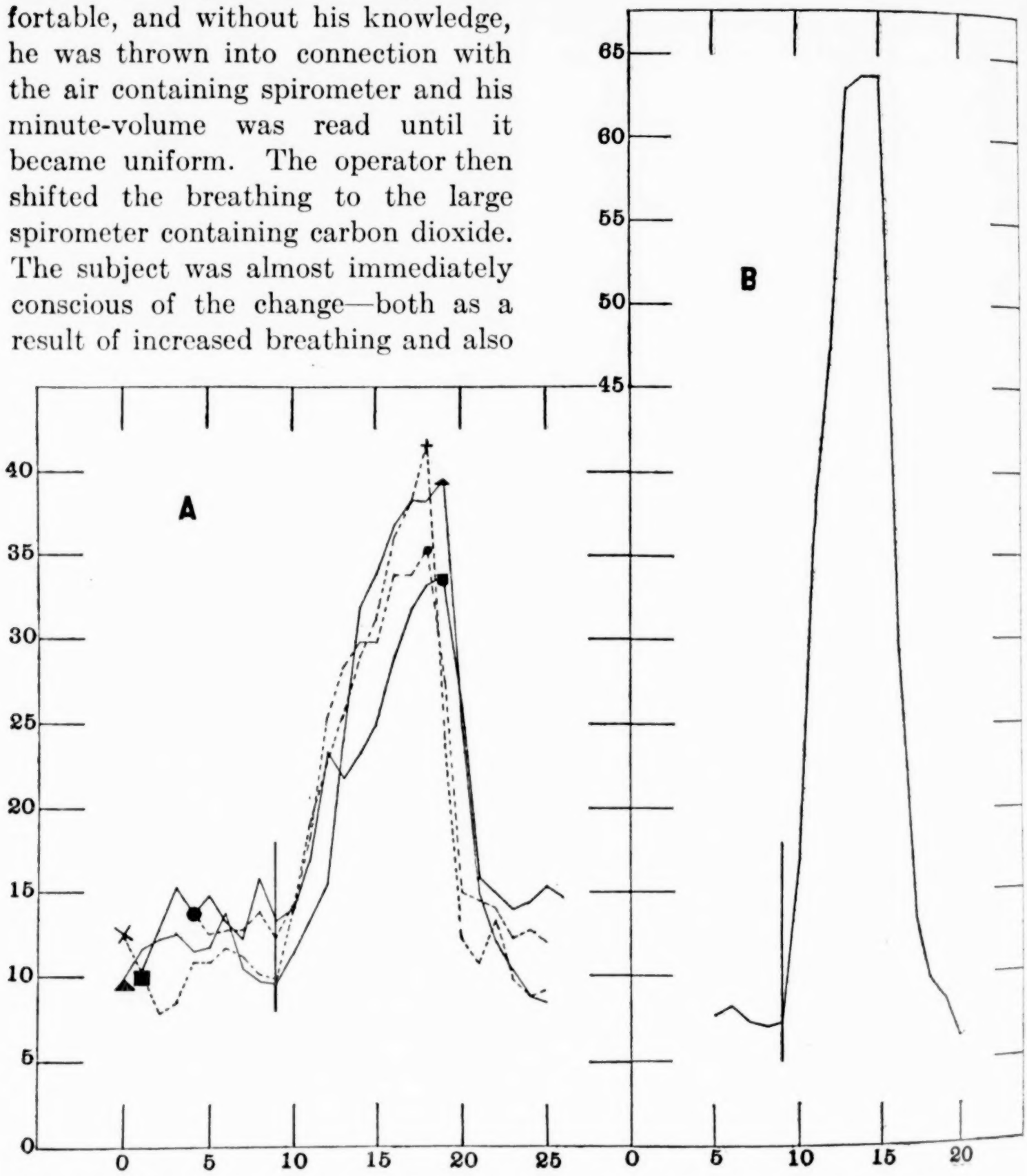

FIG. 2.—Effect on the same person of breathing 5 and 7 per cent. carbon dioxide.

A. ■, 4.97 per cent. carbon dioxide in air, March 13, A.M.; ●, 5.03 per cent. carbon dioxide in air, March 13, P.M.; ▲, 5 per cent. carbon dioxide in air, March 29, A.M.; +, 5 per cent. carbon dioxide in air, March 29, P.M.

B. 7.01 per cent. carbon dioxide in air, April 26, A.M.

Vertical lines in both curves indicate beginning of carbon dioxide inhalation. Ordinates, minute-volume in liters; abscissas, time in minutes.

observation depended upon the vigor of response in the individual and the concentration of carbon dioxide employed.

In Table 1 is found a brief summary of the results of the effect of 5 per cent. carbon dioxide in air on twenty-two subjects. There is a high degree of individual variation which cannot be correlated with height, age, weight, or any other factor we can identify. The variation is shown even more vividly in Figure 1, which gives the entire history of six of the experiments included in Table 1. The most vigorous response shown in Figure 1 was given by S. W., No. 13 in Table 1, a well-built man of medium height and weight; and the least intense response by W. S. G., No. 8, a somewhat taller and heavier man. It may be objected that the rather irregular minute-volumes on breathing air prior to carbon dioxide indicate a lack of familiarity with the apparatus which might induce irregularity of response.

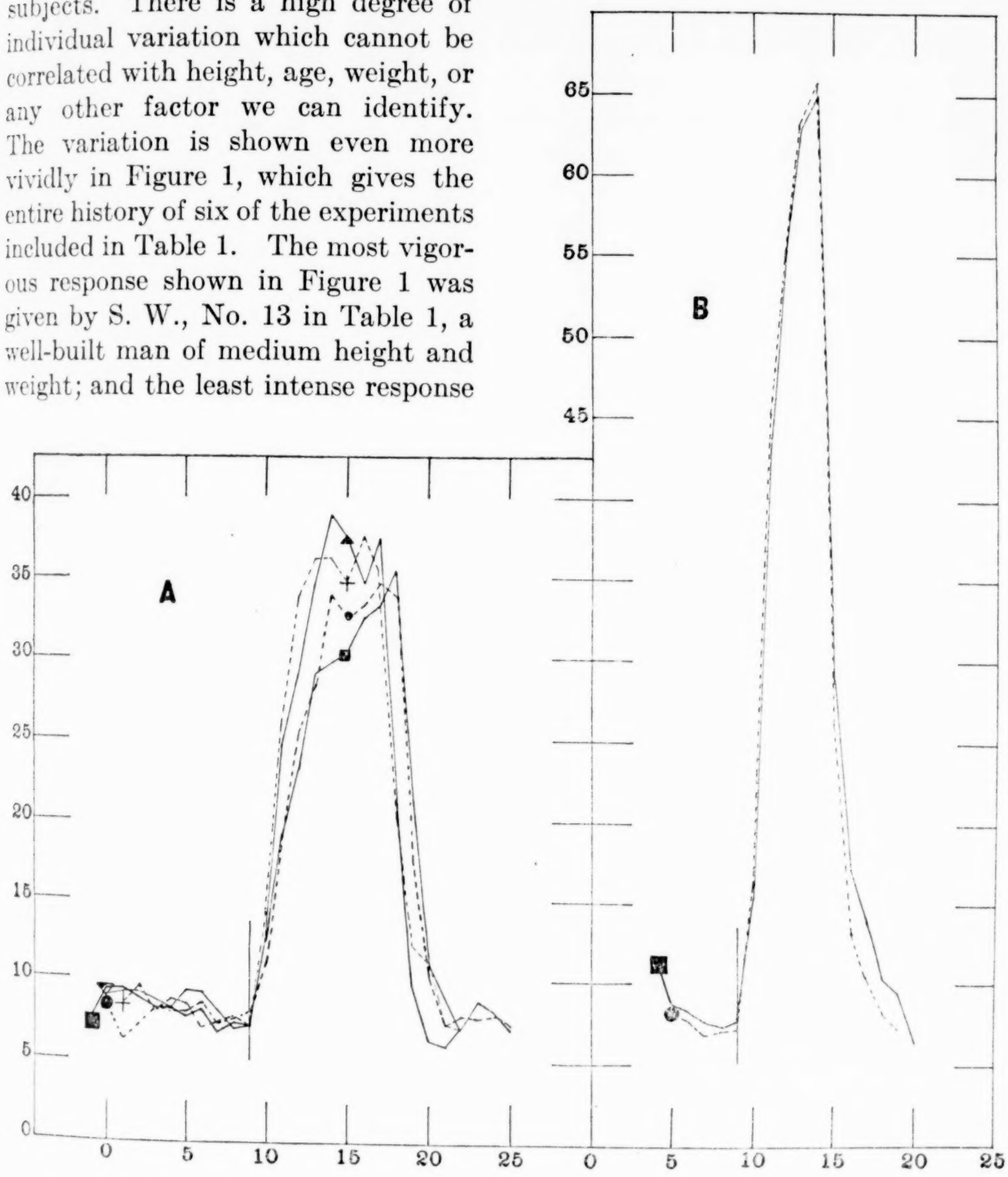

FIG. 3.—Effect on the smae person of breathing 5 and 7 per cent. carbon dioxide.

A. ■, 5.02 per cent. carbon dioxide in air, March 15, A.M.; ●, 4.94 per cent. carbon dioxide in air, March 15, P.M.; ▲, 5.02 per cent. carbon dioxide in air, April 5, A.M.; ✢, 5.05 per cent. carbon dioxide in air, April 5, P.M.

B. ■, 7.01 per cent. carbon dioxide in air, April 29, A.M.; ●, 7.01 per cent. carbon dioxide in air, April 29, P.M.

Vertical lines in both curves indicate beginning of carbon dioxide inhalation. Ordinates, minute-volume in liters; abscissas, time in minutes.

But it will be seen that the two minute-volumes immediately preceding carbon dioxide inhalation are reasonably constant, and careful perusal of all our data indicates that this rather vague reason for irregularity has no significance.

Figure 2A shows the effect of 5 per cent. carbon dioxide in air breathed by the same subject on different days. Solid lines are morning periods and dotted lines are afternoon observations on the same day. The shape of all four curves is similar. A fair amount of variation in response occurs on the two different days and appears both in the morning and in the afternoon. In Figure 2B, the reaction of the same individual to 7 per cent. carbon dioxide in air has much the same shape as that obtained with 5 per cent. carbon dioxide. There is a quick high response which contrasts markedly with the result shown in Figure 4B. The observation was made at about 10 A.M., with the intention of repeating late in the afternoon, but the experience brought on immediate headache and malaise which made it necessary to omit the afternoon observation.

Figure 3 is from findings on a man who reacted very regularly. The curves in A show the effect of 5 per cent. carbon dioxide. Solid lines are morning observations, dotted lines afternoon. Notice the fact that the variation in result between days holds for morning and afternoon just as in Figure 2A. That is to say, the setting of the person to respond to carbon dioxide varies from day to day but, so far as our experience has gone, does not change significantly on the same day. Figure 3B shows the effect of 7 per cent. carbon dioxide on the same subject. Morning and afternoon observations are practically identical.

Figure 4 shows observations upon a subject who responds but slightly to 5 per cent. carbon dioxide and presents the same type of sluggish response to 7 per cent. mixtures.

Discussion

The aspect of carbon dioxide response dealt with in this paper has been considered recently by Davies, Brow, and Binger (2) and by Padget (3). The first authors employed a rebreathing technic and studied a single subject on different days. Comparing their results with figures obtained by Peabody (4) and Scott (5), they conclude that "the respiratory response to carbon dioxide in the inspired air shows marked variations in different individuals, and indeed in any given individual on different days." Padget (3) made experiments both by rebreathing and by a technic very similar to our own—that is, the immediate breathing of carbon dioxide mixtures. He concludes: "The reaction of any one subject to the same concentration of carbon dioxide at different times is in general constant, while the reactions of different individuals vary greatly."

There can be no doubt about the variation between different persons, and it seems equally certain that the cause of the difference resides in some very fundamental feature of the organization of the individual. A subject such as the one whose reaction is shown in Figure 4 remains true to type. He will display variation in response to the same concentration of

carbon dioxide but he will not go out of his type—will not become a high-level performer like the subject of Figure 3. It would be a most interesting thing to compare two subjects of the types shown in Figures 3 and 4 in regard to every possible respiratory factor, and to determine whether the simple test of carbon dioxide response has any reasonable utility for determining physical efficiency.

The fact of the large degree of individual variation which has been observed has important bearing on the treatment of carbon monoxide poisoning by carbon dioxide inhalation. The subjects of Figures 2 and 3 attain a fourfold to fivefold increase in ventilation as a result of inhalation of 5 per cent. carbon dioxide, whereas the subject of Figure 4 gains less than a threefold increase. In severe carbon monoxide poisoning when the inhalation treatment is most needed in order to bring the patient oxygen and when the response to respiratory stimulation is depressed, the subject of Figure 4 would gain far less from the treatment than would the subject of Figure 3.

The response to 7 per cent. carbon dioxide is equally variable between different subjects, but gives assurance of vigorous stimulation in even the least reactive persons. Under the circumstances of our work, but one person out of twelve experienced headache. This was the subject of Figure 2B. His experience could be called annoying, but nothing more.

Variations in response to a single concentration of carbon dioxide shown by the same person on different days are most interesting and their cause is not known. Ordinarily the variation is not great, but occasionally one sees surprising changes. For example, one of the authors (C. K. D.) breathing 5 per cent. carbon dioxide obtained

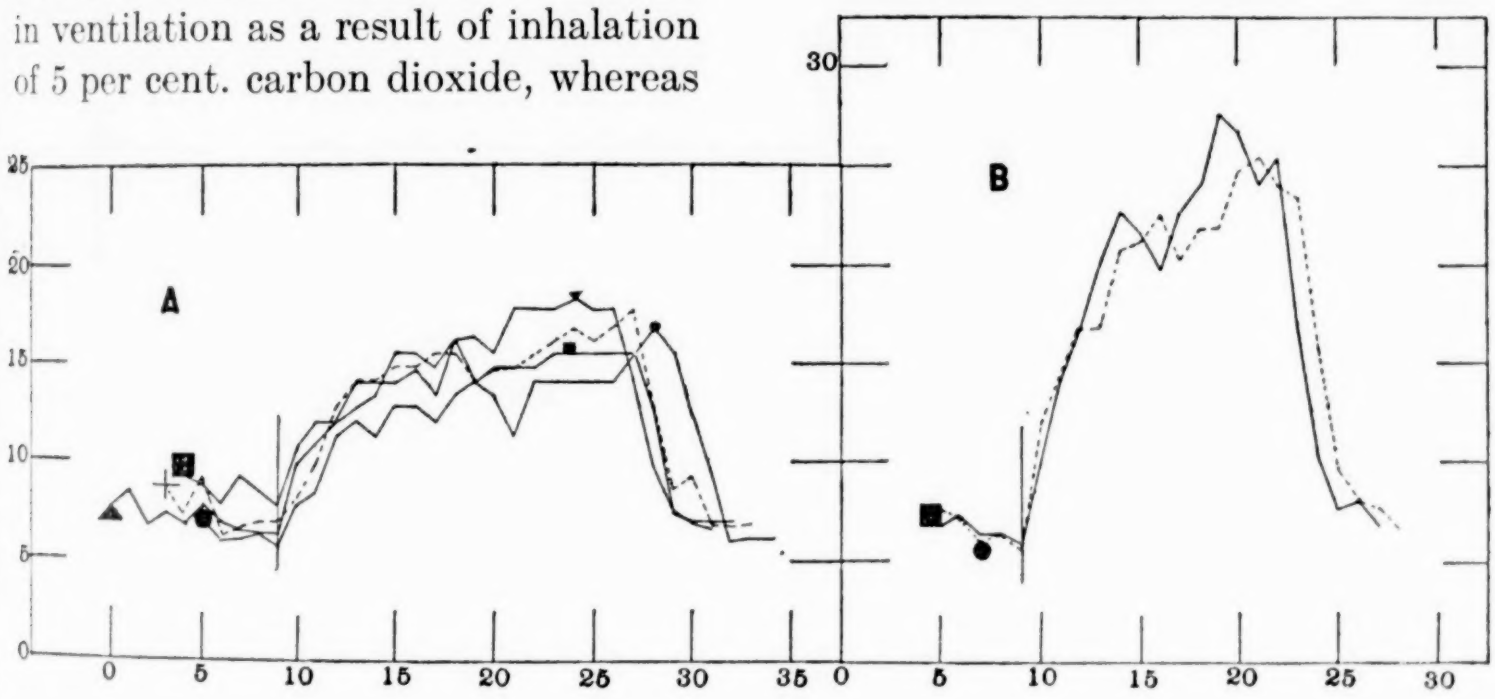

FIG. 4.—Effect on the same person of breathing 5 and 7 per cent. carbon dioxide.
A. ■, 5.03 per cent. carbon dioxide in air, March 6, A.M.; ●, 4.98 per cent. carbon dioxide in air, March 4, A.M.; ▲, 5 per cent. carbon dioxide in air, March 22, A.M.; +, 4.98 per cent. carbon dioxide in air, March 22, P.M.
B. ■, 7 per cent. carbon dioxide in air, April 17, A.M.; ●, 7.01 per cent. carbon dioxide in air, April 17, P.M.
Vertical lines in both curves indicate beginning of carbon dioxide inhalation. Ordinates, minute-volume in liters; abscissas, time in minutes.

a maximum ventilation of 25 liters a minute after ten minutes' inhalation on February 15. On January 15 the same subject had reached a ventilation of 32 liters a minute at the end of five minutes, and this had slowly increased to 37.5 liters by the twelfth minute. The minute-volume preceding inhalation on February 15 averaged 7.1 liters and was very steady. On January 15, the normal minute-volume averaged 7.8 liters and was somewhat variable. The subject was in uniform good health and was unconscious of the difference in response. Our findings agree with Padget's in failing to correlate the degree of response with the magnitude of the normal minute-volume measured just prior to carbon dioxide administration. With 7 per cent. carbon dioxide, variations in the response of the same subject occur but are not so marked as with 5 per cent. The subject seems compelled to breathe his utmost, and this again is a favorable result for the recommendation of 7 per cent. carbon dioxide in the oxygen-carbon dioxide inhalation mixture for treatment of carbon monoxide poisoning.

Summary

1. Healthy young adults at rest experience very varied degrees of response when given inhalations of 5 and 7 per cent. carbon dioxide in air.

2. In some subjects the response to 5 per cent. carbon dioxide consists in little more than a doubling of the normal minute-volume.

3. Seven per cent. carbon dioxide induces the maximal ventilation obtainable without causing undue discomfort to normal subjects.

4. The same subject breathing identical concentrations of carbon dioxide responds differently on different days but does not lose his characteristic type of response.

BIBLIOGRAPHY

1. Final Report of the Commission on Resuscitation from Carbon Monoxide Asphyxia: The Treatment of Carbon Monoxide Asphyxia. This Jour., 1923–1924, *5*, 125.
2. Davies, H. W., Brow, G. R., and Binger, C. A. L.: The Respiratory Response to Carbon Dioxide. Jour. Exper. Med., 1925, *41*, 37.
3. Padget, P.: The Respiratory Response to Carbon Dioxide. Am. Jour. Physiol., 1928, *83*, 384.
4. Peabody, F. W.: Clinical Studies on the Respiration. No. 1. The Effect of Carbon Dioxid in the Inspired Air on Patients with Cardiac Disease. Arch. Int. Med., 1915, *16*, 846.
5. Scott, R. W.: Observations on the Pathologic Physiology of Chronic Pulmonary Emphysema. *Ibid.*, 1920, *26*, 544.

THE USE OF 7 PER CENT. CARBON DIOXIDE AND 93 PER CENT. OXYGEN IN THE TREATMENT OF CARBON MONOXIDE POISONING*

CECIL K. DRINKER, M.D., AND THOMAS J. SHAUGHNESSY[1]

From the Department of Physiology, Harvard School of Public Health, Boston, Mass.

THE inhalation treatment of carbon monoxide poisoning suggested by Henderson and Haggard (1) in 1922 and widely used since 1923 has been in a curious medical position practically from the start. When adopted for field use by the Resuscitation Commission of the American Gas Association the method had ample experimental and physiologic justification. The situation which followed has, however, differed from that presented by the introduction of other therapeutic advances in that the most intensive experience with this new form of treatment has rested with laymen. Physicians see relatively few cases of carbon monoxide poisoning which are in immediate danger of death. A patient overcome by carbon monoxide from leaking gas, from automobile exhaust, or from smoke is ordinarily seen first and treated first by the employees of a public utility company, by the police, or by firemen. Police and fire department surgeons have opportunity to see a certain number of such patients when they are critically saturated with carbon monoxide. The same is true for industrial physicians in plants possessing a carbon monoxide hazard. But taking carbon monoxide poisoning as a whole, the physician most often finds a patient who either is dead or has begun to lose carbon monoxide and emerge from real danger. If the inhalation treatment is in use, it is continued and the doctor does all in his power to safeguard recovery. He has not seen the patient when first brought clear of gas, with breathing practically gone and desperately near death, and he has had no opportunity to judge whether the inhalation has stimulated breathing and started recovery.

Owing, we believe, to this more or less inevitable separation of the medical profession from the most acute aspects of carbon monoxide asphyxia, there has been but little critical clinical comment upon the procedure. Physicians have realized the rationality of the treatment, have seen it work well in promoting the final stages of recovery, and have let it go forward unpolished by the testing and the comment which greet other advances in treatment susceptible to complete observation under hospital surroundings.

*Received for publication Oct. 4, 1929.

[1] Supervisor of Resuscitation and Instruction, Committee on Resuscitation and Related Activities, Liability Insurance Fund, Consolidated Gas Company of New York and its Affiliated Gas and Electric Companies.

It may be contended that, as a result of this somewhat anomalous situation, practically any sort of attractive mechanical device could be given wide vogue for the treatment of asphyxia. That such might be the case for a brief period, if the appliance had medical endorsement, is undoubtedly true. It must, however, be remembered that first aid men in the utility companies were the first to awake to the inadequacy of the pulmotor and bring about thorough medical examination of the appliance. The authors have had an unusual opportunity to realize the intelligence and expertness of lay emergency crews in dealing with carbon monoxide poisoning—crews that for years have had at their disposal every available advance in the art of resuscitation. No doubt can exist that in the judgment of these men the inhalation treatment has constituted a signal advance in technic. Nor are we aware of reports from physicians, who have dealt with actual cases of poisoning, which indicate either immediate harmful effects or the possibility of unfortunate sequelae attributable to the treatment.

There has been a certain amount of adverse comment during the past six years. This is based upon theoretical or experimental data, not upon actual observations upon patients. Since our experience causes us to recommend 7 per cent. instead of 5 per cent. carbon dioxide in the inhalation mixture, we believe it worth while to present this comment in detail, together with our reasons for disregarding it and urging the use of a higher concentration of carbon dioxide in the initial stages of treatment.

Rossiter (2), physician to the Carnegie Steel Company, in a pamphlet printed privately and giving his own experience with carbon monoxide poisoning, makes the following statements:

> In view of the above facts, Henderson and Haggard have proposed a new form of treatment which consists of administering Carbon Dioxide (5%) with oxygen during the artificial respiration. The Carbon Dioxide acts as a respiratory stimulant causing the respirations to become stronger and deeper thus allowing full ventilation of the lungs which displaces Carbon Monoxide in the blood.
>
> Although they claim patients are resuscitated much quicker by this method, yet it must be remembered that most of their experiments and experience has been on cases where the blood saturation was between 40 and 50%. No doubt the Carbon Dioxide does increase the rate and depth of the respirations but where the percentage of saturation has been over 50% and continued so, for any length of time, the heart is weakened by the oxygen-deprivation and this sudden stimulus may cause it to fail. Henderson, himself, states that the only risk in this treatment was the action on the heart but that this was overcome by giving a dose of atrophine and reducing the percentage of Carbon Dioxide. Dr. R. R. Sayers of the Bureau of Mines and Dr. Nicloux of the University of Strasbourg, France, claim they found this method no better than the results obtained by giving pure oxygen.

Sayers and Yant (3) make a more explicit comment upon the same matter:

> Henderson states that breathing CO_2-O_2 mixtures produces an increase in blood pressure. This probably causes an increase of flow of blood through the lungs, and would thus aid in the elimination of CO_2; but in victims that have been gassed over a comparatively long period (several hours), the heart might perhaps be weakened and unable to withstand the increased stimulation for breathing caused by the CO_2. However, if the patient is under constant

observation, overstimulation may be avoided by temporarily stopping the use of the CO_2-O_2 mixture.

None of these conjectures as to circulatory danger can be supported by the facts as we know them today. Inhalation of 5 or 7 per cent. carbon dioxide in a resting subject is accompanied by but slight increase in blood pressure and volume delivery of blood by the heart. The situation is not at all analogous to that which occurs when carbon dioxide accumulates in the body during exercise. One of us has repeatedly watched the beneficial effects of the inhalation of 5 per cent. carbon dioxide and 95 per cent. oxygen in animals profoundly gassed, and has been impressed by the improvement in cardiac activity and circulatory condition which takes place.

It is quite true that in advanced carbon monoxide poisoning the heart dilates (4), the cardiac output begins to fail, and the blood pressure falls. These are, however, the nonspecific symptoms of circulatory failure from lack of oxygen and from many other causes. If the heart has dilated considerably, it may remain so for several days (5), and it is this fact which causes the admonition to keep all cases of asphyxia at rest for some time after the accident. But the knowledge that the heart is thus affected by advanced carbon monoxide poisoning is of itself a strong argument for the use of the oxygen-carbon dioxide treatment. Carbon dioxide dilates the blood vessels of the heart, permitting improvement in the oxygenation and nutrition of the organ, and to a moderate degree increases the flow of blood into the heart. There is practical evidence for the favorable effect of the inhalation treatment on a failing circulation from several sources. Most noticeable is the widespread use of carbon dioxide inhalations to de-etherize patients after surgical operations. E. Levi (6), in Florence, Italy, first used this method, employing 5 to 20 per cent. carbon dioxide with oxygen, and makes a particular point of the favorable effects upon the heart. In 1920, Henderson, Haggard, and Coburn (7) used 6 to 10 per cent. carbon dioxide in air and report excellent effects in cases where the circulation was bad.

A second line of evidence bearing upon the safety of the inhalation treatment for the heart and circulation comes from actual experience in the treatment of carbon monoxide poisoning. In 1925, an inquiry of all the users of inhalation apparatus (300 at that time) brought 180 replies. While the greater number of these were returned by nonmedical men, physicians' findings were frequently reported. In no instance was word received of the immediate collapse of seriously gassed patients as the inhalation treatment was begun. There are now at least 1,000 users of the inhalation method in this country. No reports of sudden death or of circulatory failure with the institution of the treatment have appeared. The issue feared by Rossiter and by Sayers and Yant is not one of subtle medical distinctions. If the heart of a critically gassed patient were unfavorably affected by the inhalation treatment, the result would not be a matter of a few missed beats, of irregularity, or of further dilatation. It would be death, for such patients are frequently at the very edge of death when they

first receive treatment. And death would be so directly related to the beginning of inhalation as to cause immediate comment. In New York City we have opportunity to follow the successful treatment of between 600 and 800 cases of carbon monoxide poisoning yearly. In about an equal number of cases death results, over 95 per cent. of this number being dead when discovered. During four such years of experience we have no records of sudden death during inhalation, and it is impossible to consider that the precautions in the use of the treatment urged by Rossiter and by Sayers and Yant in the early days of the method need be regarded today. This assertion may be made with equal validity for both 5 and 7 per cent. carbon dioxide in oxygen. Much higher concentrations of carbon dioxide than 7 per cent. have been observed to have no unfavorable effect on the heart and circulation of animals poisoned by carbon monoxide; they have been used for de-etherization in human beings and for the treatment of asphyxia in the newborn; and, finally, in the actual treatment of 300 cases of gas poisoning, three of morphine poisoning, and nine of drowning, by 7 per cent. carbon dioxide in 93 per cent. oxygen, no bad effects have been observed.

A more interesting criticism of the inhalation treatment is the contention that carbon monoxide leaves the blood as rapidly when pure oxygen is inhaled as when oxygen-carbon dioxide mixtures are employed and that, consequently, upon the grounds of both the greater availability of pure oxygen and the expense attending the use of oxygen-carbon dioxide mixtures, the latter should be discarded.

Sayers, in a note appended to a report published by one of us (8) in December, 1925, writes as follows:

> In our experimental work on men and on animals we found that breathing oxygen removed carbon monoxide from the blood about four times faster than did breathing air and that the carbon dioxide-oxygen mixture removed it about five times faster than did air. However, our experience with both men and animals indicates that the carbon dioxide-oxygen mixture gives no better results than does pure oxygen when judged by the time necessary for recovery after a given exposure to carbon monoxide and a given blood saturation and the condition of the animal or victim after treatment is about the same. The use of oxygen is far more practicable in the mining industry than is the carbon dioxide-oxygen mixture.

Nicloux, Nerson, Stahl, and Weill (9) poisoned dogs very severely and rapidly with pure carbon monoxide and determined the rate of removal of the gas from the blood when the animals breathed (*a*) air, (*b*) air plus 5 per cent. carbon dioxide, (*c*) oxygen, and (*d*) 95 per cent. oxygen and 5 per cent. carbon dioxide. They report very few observations and find but slight difference between the efficacy of oxygen alone and oxygen plus carbon dioxide. The latter mixture was admittedly better than oxygen, but so little better as to fail to commend it to these French workers. The paper is brief and includes no observations upon the dogs except the series of measurements on carbon monoxide disappearance from the blood. The experiments cannot be compared, as the French authors do, with work on dogs of similar type by Henderson and Haggard, since the latter investigators used 8 to 10 per cent. carbon dioxide with oxygen. If one takes the

evidence without comment, it is shown not that the oxygen-carbon dioxide mixture should be discarded but that in the carbon dioxide concentration used for human rescue work it is, perhaps, less efficacious for getting carbon monoxide out of the blood of dogs than has been believed. A later paper by Nicloux (10) reviews the same experiments and advises continued observation of the effects of oxygen alone and of oxygen-carbon dioxide mixtures.

Walton, Eldridge, Allen, and Witherspoon (11), working at the Edgewood Arsenal to determine whether the Naval Department should use oxygen alone or the oxygen-carbon dioxide mixture, obtained results identical with those of Nicloux and his collaborators. The experiments were upon dogs and utilize the disappearance of carbon monoxide from the blood as the sole criterion of successful treatment. The dogs were divided into six groups of ten each and breathed pure carbon monoxide in air for an hour to an hour and a half—much longer than in the experiments of Nicloux. Walton and his associates conclude:

> 1. In dogs suffering from carbon monoxid asphyxia the difference in elimination time between oxygen treated and oxygen plus 5 per cent. carbon dioxid treated subjects is slight.
>
> 2. Since the rate of elimination under pure oxygen is almost as rapid as with the oxygen plus 5 per cent. carbon dioxid and since the oxygen treatment is more readily available it is recommended that its use be continued, particularly in localities where transportation is difficult.
>
> 3. The air plus 5 per cent. carbon dioxid treatment should be of value for rescue parties sent to inaccessible mines and especially in military operations.

Here again the final opinion is that, judged upon the criterion of carbon monoxide removal, the oxygen-carbon dioxide treatment is not significantly better than oxygen alone. The authors also report:

> No variation was noted in the after effects of the different treatments. There was no increased tendency toward paralysis in any particular group, and it would be impossible to tell from the after history of the dogs what treatment they had received.

It is an unavoidable defect of experiments upon animals that unfortunate effects escape record. The animal cannot complain of headache, persistent nausea, and disability; yet these are after effects of gassing which are familiar to us all. In reports upon experimental work on men poisoned voluntarily with carbon monoxide, Sayers and Yant (3) and Sayers (12) declare that after the use of oxygen alone, patients are more comfortable than if given the oxygen-carbon dioxide treatment, this being emphatically true when 8 to 10 per cent. carbon dioxide was used. On the other hand, Henderson and Haggard (1) report the opposite. So far as we can gather from numerous records received from users of inhalation apparatus, there are no unfortunate after effects from the use of the 5 per cent. carbon dioxide-oxygen mixture now employed. Indeed, the reverse is true, and there is today extensive employment of the inhalation treatment for mild cases of gassing in order to remove the possibility of disability and lost time. It may be contended that the same result would be obtained with oxygen alone, had the procedure anything like the extensive use and observation now accorded the oxygen-carbon dioxide treatment. We believe it

justifiable to doubt this. Oxygen alone does not stimulate breathing, cannot be breathed voluntarily for any length of time in the volume in which the oxygen-carbon dioxide mixture must involuntarily be taken. Furthermore, there are data of entire physiologic validity indicating the especial appropriateness of carbon dioxide for restoring the normal chemical equilibrium of the body after carbon monoxide anoxemia, and these data have been entirely disregarded both by Nicloux and by Walton and his collaborators. It is not enough, in considering the efficacy of the oxygen-carbon dioxide treatment, to use the disappearance of carbon monoxide from the blood as the sole criterion for evaluating the procedure. While saturation of the red coloring matter of the blood with carbon monoxide and consequent oxygen lack is the obvious and best known feature of poisoning, it happens that this very event induces other changes which must return to normal before complete recovery can be secured, and these changes are intimately concerned with carbon dioxide.

Haldane (13), in 1924, described an experiment in point. A mouse in a glass container was subjected to a current of air containing 0.3 per cent. carbon monoxide. Within three minutes the animal was quite helpless. If, now, a current of air containing 4 to 5 per cent. carbon dioxide was blown in, the mouse waked up, raised its head, and began to move about, though feebly. When pure air was again supplied to the intake, the mouse sank down again into its former helpless state. The contrast was very striking. The arrangement of the experiment kept the concentration of carbon monoxide in the container at exactly the same level all the time and there was a pronounced betterment in the condition of the animal by the addition of carbon dioxide to the atmosphere of the container. Haldane explained this effect as due to the favorable action of carbon dioxide in dilating the smaller blood vessels and so permitting a freer liberation of such oxygen as the blood was still able to carry. The experiment is dramatic and indicates the peculiar fitness of carbon dioxide to meet the situation caused by carbon monoxide.

Haggard and Henderson (14) showed that the excessive breathing which occurs in the early stages of carbon monoxide poisoning depletes the normal store of body carbon dioxide, and in order to maintain the reaction of the blood at the neutral point, alkali—in this case sodium bicarbonate—must move into the tissues. It is possibly this abnormal migration of alkali which is at the bottom of the circulatory derangement mentioned by Haldane in his explanation of the favorable effects of carbon dioxide.

There can be no argument upon the wisdom of using carbon dioxide inhalations to bring to normal the fundamental derangement inherent in such an alteration of the chemical equilibrium of the body. When a dose of mercuric chloride is taken, the first thing to do is to get as much of the poison out of the body as can be removed, and to do this as quickly as possible. There is then a secondary battle of equal importance, the allaying of symptoms referable to the action of the bichloride. The same point

may be made in regard to carbon monoxide poisoning. The gas must be removed from the blood as fast as possible, and there is no doubt that the oxygen-carbon dioxide mixture now in use does this more rapidly than oxygen alone. The disagreement which has arisen does not deal with the truth of this statement but with the degree of superiority inherent in the oxygen-carbon dioxide mixture. During and possibly even after the removal of most of the carbon monoxide, carbon dioxide is apparently the ideal substance to readjust the body to its normal state.

The experiments of Nicloux (9) (10) and those of Walton (11) contain no data on the acid-base situation in the blood at the moment of instituting treatment, and do not present even a rough estimate of what may be called the respiratory ability of the animal at the moment when treatment was begun. Stadie and Martin (15), in a careful repetition of work done by Douglas, Haldane, and Haldane (16), showed that any tendency of the blood to become alkalinized causes it to seize and hold carbon monoxide with even more than normal avidity and also to fail to give up readily such oxygen as may still be carried. Conversely, anything which increases the hydrogen ion concentration of the blood will hasten the elimination of carbon monoxide.

In general summary, we feel the following to be a fair statement of the status of the inhalation procedure at the present time:

1. Dangers to the circulation very properly mentioned by Henderson and Haggard when the inhalation treatment was first started, and reiterated by Rossiter and by Sayers and Yant, need no longer be considered. Upon the basis of both experimental and clinical observations, the oxygen-carbon dioxide inhalation is beneficial to the circulation rather than harmful, and this is true in carbon dioxide concentrations as high as 7 per cent.

2. On the basis of animal experimentation, Nicloux and his collaborators, and Walton and his collaborators present data, solely upon the release of carbon monoxide from the blood, which indicate that inhalation mixtures of oxygen and carbon dioxide, while better than oxygen alone, are not so decidedly superior as shown in the earlier papers of Henderson and Haggard.

3. When all the possible effects of carbon dioxide for restoration of the normal physicochemical equilibrium in the body are considered, carbon dioxide possesses an importance which would make it most unwise to discontinue its use in carbon monoxide poisoning.

4. The data cited, together with observations (17) on the inhalation of 5 and 7 per cent. concentrations of carbon dioxide by normal individuals, have indicated to us the advisability of increasing the concentration of carbon dioxide in the inhalation mixture from 5 to 7 per cent.

Field Observations upon the Use of 7 Per Cent. Carbon Dioxide and 93 Per Cent. Oxygen in Treating Carbon Monoxide Poisoning

Since 1925, we have had opportunity to observe the use of 5 per cent. carbon dioxide and 95 per cent. oxygen for carbon monoxide poisoning by the

emergency crews of the Consolidated Gas Company of New York. At the present time there are ten emergency trucks manned by crews of three. They respond to all notifications of leaking gas, to fires, and to all sorts of situations where asphyxia has occurred or is a hazard. The personnel of these crews changes but little. All the men are thoroughly drilled in giving artificial respiration, in handling unconscious patients, and in the use of inhalation apparatus. They have had instruction in the nature of carbon monoxide poisoning and other common types of asphyxia, and have been shown the value and necessity of making simple clinical observations on each case. It is certain that no group of men in the world has such a constant and large experience with carbon monoxide poisoning. In 1926, 789 patients were treated and recovered; in 1927, 715; and in 1928, 850. Owing to the fact that approximately 60 per cent. of the cases are suicidal, the number found dead on arrival is large, slightly exceeding the number revived.

The men on the emergency crews have been trained to report all this experience upon the form shown in Figure 1, and have thus supplied a large volume of experience with which to contrast the alteration in practice introduced in March, 1929. At that time two crews were furnished tanks of 7 per cent. carbon dioxide and 93 per cent. oxygen, with instructions to begin treatment with a tank of this 7 per cent. mixture and to shift to the old 5 per cent. concentration when the first tank was empty. This has meant from five to twenty minutes' inhalation of 7 per cent. carbon dioxide in oxygen.

From the discussion in the beginning of this paper, some of the reasons for recommending this change have been gained. There are, however, two other important facts bearing upon the change. First of all, it has been found that the increase in breathing experienced by normal persons who inhale 5 per cent. carbon dioxide is not uniform. That is, we cannot say that this concentration will always triple or even further increase the breathing. In a series of normal men and women tested during the past spring it was found that the effect of 5 per cent. carbon dioxide varied in different persons from less than a twofold to a fivefold increase in respiration (17). The reasons for this variability are quite unknown. When 7 per cent. carbon dioxide is used, the variability persists, but all persons respond on a higher level, so that breathing is always doubled and may show even a sevenfold increase, the usual result being respiration five times normal. It is obvious that a patient whose breathing under normal conditions increases not more than one and one-half times when given 5 per cent. carbon dioxide, will gain little from the usual inhalation treatment. If, however, he is given 7 per cent. carbon dioxide, he will experience a greater augmentation of respiration and will have a better chance to gain oxygen and to lose carbon monoxide. A second fact makes it additionally important to use the 7 per cent. inhalation mixture in the early stages of treatment. Recent experiments by one of us have shown that as carbon monoxide asphyxia develops, the response to carbon dioxide stimulation becomes less. This is unimportant in mild poisoning but when

_____ GAS COMPANY _____ Dept. Station
(Print Company)

ASPHYXIATION REPORT

Date of Accident.....
Name.....Address.....
Age.....Sex.....Married or Single.....Nationality.....
Kind of premises.....
Number of floor or apartment.....
Condition prior to asphyxiation.....
Condition when discovered: Conscious or unconscious.....
Breathing—Rate per minute.....
General Character (Check type observed)—Gasping and slow—Shallow—Rapid and weak—Increased.....
.....
Pulse—Rate per minute.....
General Appearance of Patient.....
Condition at end of Treatment.....
Breathing.....
Pulse.....
General.....
.....
.....
Condition Next Day.....
.....
.....
Time and by whom discovered.....
Time last seen or heard.....
Where did gas come from (describe fully fixture or appliance).....
.....
.....
.....
If leak, where was it.....
Time of arrival of ambulance from.....
Name of attending doctor.....
Length of time Prone Pressure Method applied before arrival of Inhalator.....
By whom.....
Length of time Prone Pressure Method applied in conjunction with Inhalator.....
By whom.....
Length of time application of Inhalator.....
Fatal.....Recovered.....
Was gas supply discontinued by you.....
Where does meter set.....
How many kinds of gas appliances used.....
Size of room.....Height of ceiling.....
How many doors.....How many windows.....
Report fully facts and circumstances.....
.....
.....
.....
Date of report..... Signed.....

FIGURE 1

patients are seriously affected and need oxygen at once, it must be understood that their ability to have the breathing stimulated by carbon dioxide is lowered, and in order to get the desired breathing the concentration of carbon dioxide must be increased.

Up to the present date, Sept. 25, 1929, 300 patients have been treated with 7 per cent. carbon dioxide and 93 per cent. oxygen. Emergency crews use a tank containing this mixture and when after a brief period, depending upon the depth of the breathing, this first tank is emptied they use 5 per cent. carbon dioxide and 95 per cent. oxygen to complete the treatment. In certain instances this last mixture has failed to give adequate breathing and the 7 per cent. mixture has again been used. There has been one death, which occurred thirty-one hours after the beginning of treatment. This patient received 7 per cent. carbon dioxide in oxygen for eight minutes and then the 5 per cent. mixture at intervals during the ensuing period. The individual was profoundly poisoned, never regained consciousness, and died slowly as is so often the case when protracted anoxemia has produced serious neurologic damage.

The following reports will indicate the nature of our experience and the clinical utility of the 7 per cent. mixture.

The last case, that of C. L., is particularly interesting for the manner in which it duplicates Haldane's mouse experiment (p. 306). The return of consciousness under high carbon dioxide and loss of consciousness under lower concentration is striking.

Date:
Address:

Name: *T. S.*
Age: *67*
Sex: *Male*
Condition prior to asphyxiation: *Good health*
Condition when discovered—conscious or unconscious: *Unconscious*
Breathing—rate per minute: *14* ✓
General character—(check type)—gasping & slow—shallow—rapid & weak—increased
Pulse—rate per minute: *Not counted*
General appearance of patient: *Very bad*
How long was 93% oxygen and 7% CO_2 applied: *20 minutes first time*
5 minutes later
Did breathing increase: *Yes* To what rate: *At 5:15 rate 14*
At 5:25 rate 18
At 5:35 rate 22
What was the type observed at this time: *Good deep breaths*
How long was 95% oxygen and 5% CO_2 applied: *1 hour and 5 minutes*
How long after beginning of treatment did the patient recover consciousness: *2 hours*
Inquire if patient has headache—(check type)—slight—severe: *Not recorded*
Time of arrival of ambulance: *5:20 p.m.* What hospital: *Bellevue*
Doctor's name: *Dr. B.*
Did the doctor make any comment: *Considered rate of recovery very remarkable in view of the patient's condition*

Was prone pressure necessary in this case: *No* How long:
Do you think patient recovered consciousness more rapidly with the 7% CO_2 treatment:
Cannot say
State other things of interest that occurred:

Respiration Report

Time	*Respiratory Rate*	*Treatment*
5:15	14	7% CO_2 and 93% O_2 began
5:25	18	7% CO_2 and 93% O_2
5:35	22	7% CO_2 and 93% O_2
5:35–6:00		5% CO_2 and 95% O_2
6:00	18	5% CO_2 and 95% O_2
6:05–6:10		7% CO_2 and 93% O_2
6:10	23	
6:10	Turned back to	5% CO_2 and 95% O_2
6:15	25	5% CO_2 and 95% O_2
6:25	26	5% CO_2 and 95% O_2
6:35	28	5% CO_2 and 95% O_2
6:35–6:55		No inhalation
6:55	26	5% CO_2 and 95% O_2
7:00	28	5% CO_2 and 95% O_2
7:10	28	5% CO_2 and 95% O_2

At 7:10 patient could move freely and talk.

Date: *April 27, 1929*
Name: *A. L.* Address:
Age: *40*
Sex: *Male*
Condition prior to asphyxiation: *Good health*
Condition when discovered—conscious or unconscious: *Unconscious*
Breathing—rate per minute: *8* ✓ ✓
General character—(check type)—gasping & slow—shallow—rapid & weak—increased
Pulse—rate per minute: *120*
General appearance of patient: *Poor*
How long was 93% oxygen and 7% CO_2 applied: *30 minutes*
Did breathing increase: *Yes* To what rate: *32*
What was the type observed at this time: *Patient breathing normal. Still unconscious*
How long was 95% oxygen and 5% CO_2 applied: *3 hours*
How long after beginning of treatment did patient recover consciousness: *At the end of 3 hours patient was semi-conscious. Doctor said crew could do no more*
Inquire if patient has headache—(check type)—slight—severe:
Time of arrival of ambulance: *About 7: 50 a.m.* What hospital: *Bellevue*
Doctor's name: *Dr. H.*
Did doctor make any comment: *No*
Was prone pressure necessary in this case: *No* How long:
Do you think patient recovered consciousness more rapidly with the 7% CO_2 treatment:
Yes
State other things of interest that occurred: *While applying inhalator with 93% O_2 and 7% CO_2 for 10 minutes, noticed patient's breathing increased. Continued same for 20 minutes more when doctor requested crew to go to Bellevue. Crew applied 95% O_2 and 5% CO_2 for 3 hours when Dr. W. pronounced patient out of danger, but still in coma and left in Emergency Ward.*

Date: *June 11, 1929*
Name: *F. C.* Address:
Age: *46*
Sex: *Female*
Condition prior to asphyxiation: *Good health*
Condition when discovered—conscious or unconscious: *Unconscious*
Breathing—rate per minute: *8* ✓ ✓
General character—(check type)—gasping & slow—shallow—rapid & weak—increased
Pulse—rate per minute: *124*
General appearance of patient: *Pale, lips blue*
How long was 93% oxygen and 7% CO_2 applied: *45 minutes*
Did breathing increase: *Yes* To what rate: *30*
What was the type observed at this time: *Deep and regular*
How long was 95% oxygen and 5% CO_2 applied: *3 hours*
How long after beginning of treatment did patient recover consciousness: *3 hours and 15 minutes* ✓
Inquire if patient has headache—(check type)—slight—severe
Time of arrival of ambulance: *As crew arrived* What hospital: *St. Vincents*
Doctor's name: *Dr. M.*
Did doctor make any comment: *No*
Was prone pressure necessary in this case: *No* How long:
Do you think patient recovered consciousness more rapidly with the 7% CO_2 treatment: *Yes*
State other things of interest that occurred: *After applying 93% O_2 and 7% CO_2 for 20 minutes, patient's breathing rose to 18. I then turned on 95% O_2 and 5% CO_2, and patient's breathing came down to 12 per minute and stayed that way for about 10 minutes. I then switched back to 93% O_2 and 7% CO_2 for 25 minutes and the patient's breathing came up to 24; and then started giving 95% O_2 and 5% CO_2 for 3 hours, when patient regained consciousness, breathing 30 per minute.*

Date: *April 1, 1929*
Name: *C. L.* Address:
Age: *20*
Sex: *Male*
Condition prior to asphyxiation: *Good health*
Condition when discovered—conscious or unconscious: *Unconscious*
Breathing—rate per minute: *16* ✓ ✓
General character—(check type)—gasping & slow—shallow—rapid & weak—increased
Pulse—rate per minute: *Not taken*
General appearance of patient: *Chalky color*
How long was 93% oxygen and 7% CO_2 applied: *5 minutes*
Did breathing increase: *Yes* To what rate: *20*
What was the type observed at this time: *Patient lively and making motions to rise*
How long was 95% oxygen and 5% CO_2 applied: *10 minutes*
How long after beginning of treatment did patient recover consciousness: *About 10 minutes*
Inquire if patient has headache—(check type)—slight—severe: *Refused to talk*
Time of arrival of ambulance: *6:55 a.m.* What hospital: *Bellevue*
Doctor's name: *Dr. B.*
Did doctor make any comment: *No*
Was prone pressure necessary in this case: *No* How long:
Do you think patient recovered consciousness more rapidly with the 7% CO_2 treatment: *Yes*
State other things of interest that occurred: *On arrival found C. L. lying on floor unconscious from gas poisoning. Applied 93% O_2 and 7% CO_2 at once for 5 minutes when patient began kicking and wanted to rise. Turned on to 95% O_2 and 5% CO_2 for about 5 minutes and patient fell into a semi-conscious condition. Again turned on 93% O_2 and 7% CO_2 for about 3 or 4 minutes and patient sat up but refused to talk.*

Conclusions

1. A study of the experience since 1923 in the use and experimental examination of the effects of 5 per cent. carbon dioxide and 95 per cent. oxygen in the treatment of carbon monoxide poisoning has indicated the wisdom of increasing the concentration of carbon dioxide to 7 per cent. for the first five to twenty minutes of treatment. The principal reasons for making this change are:

a. The fact that a certain number of persons respond to carbon dioxide stimulation of breathing with comparatively slight increase when 5 per cent. carbon dioxide is used, whereas with 7 per cent. there is satisfactory augmentation.

b. Response to carbon dioxide stimulation is lowered in dangerous carbon monoxide poisoning, and a 7 per cent. concentration is a better means of securing an increase in breathing of real consequence to the patient.

c. No experimental or clinical evidence has appeared indicating that the increase in carbon dioxide to 7 per cent. carried with it the slightest danger. Indeed, all facts point to benefit to the circulation from 7 per cent. carbon dioxide in 93 per cent. oxygen.

2. Three hundred cases of carbon monoxide poisoning have been treated by employing an initial inhalation of 7 per cent. carbon dioxide and 93 per cent. oxygen for from five to twenty minutes, and completing the treatment with the usual 5 per cent. carbon dioxide mixture.

The results of this field work have been uniformly good. Breathing is more active, consciousness returns more rapidly, and after effects have not been noteworthy. It is our intention to continue this technic in emergency work for the Consolidated Gas Company of New York.

BIBLIOGRAPHY

1. Henderson, Y., and Haggard, H. W.: The Treatment of Carbon Monoxid Asphyxia by Means of Oxygen + CO_2 Inhalation. Jour. Am. Med. Assn., 1922, *79*, 1137.
2. Rossiter, F. S.: Carbon Monoxide Gas Poisoning. Carnegie Steel Company, Pittsburgh, Pa., 1928, pp. 38.
3. Sayers, R. R., and Yant, W. P.: The Elimination of Carbon Monoxide from Blood, by Treatment with Air, with Oxygen, and with a Mixture of Carbon Dioxide and Oxygen. U. S. Pub. Health Rep., 1923, *38*, 2053.
4. Zondek, H.: Herzbefunde bei Leuchtgasvergiftung. II. Mitteil. Deutsch med. Wchnschr., 1920, *46*, 235.
5. Zondek, H.: Herzbefunde bei Leuchtgasvergifteten. I. Klinischer Teil. *Ibid.*, 1919, *45*, 678.
6. Levi, E.: The Clinical Use of Carbon Dioxid with Oxygen. Jour. Am. Med. Assn., 1912, *58*, 773.
7. Henderson, Y., Haggard, H. W., and Coburn, R. C.: The Therapeutic Use of Carbon Dioxid after Anesthesia and Operation. *Ibid.*, 1920, *74*, 783.
8. Drinker, C. K.: The Efficiency of the Oxygen-Carbon Dioxide Treatment of Carbon Monoxide Poisoning. This Jour., 1925, *7*, 539.
9. Nicloux, M., Nerson, H., Stahl, J., and Weill, J.: Sur l'élimination de l'oxyde de carbone après intoxication grave: Influence de la respiration de l'air ou de l'oxygène additionnés de 5 p. 100 d'acide carbonique. Compt. rend. Soc. de biol., 1925, *92*, 178.
10. Nicloux, M.: L'oxyde de carbone et l'hygiène. Ann. d'hyg., 1926, *4*, 637.
11. Walton, D. C., Eldridge, W. A., Allen, M. S., and Witherspoon, M. G.: Carbon Monoxid Poisoning. A Comparison of the Present Methods of Treatment. Arch. Int. Med., 1926, *37*, 398.

12. Haggard, H. W., and Henderson, Y.: The Treatment of Carbon Monoxid Poisoning. Jour. Am. Med. Assn., 1921, *77*, 1065. (R. R. Sayers expresses his opinion on the after results of various treatments in the discussion of this paper.)
13. Haldane, J. S.: The Use of Carbon Dioxid as a Remedy in Gas Poisoning. Colliery Guardian, 1924, *128*, 1633.
14. Haggard, H. W., and Henderson, Y.: Hemato-Respiratory Functions. XII. Respiration and Blood Alkali during Carbon Monoxide Asphyxia. Jour. Biol. Chem., 1921, *47*, 421.
15. Stadie, W. C., and Martin, K. A.: The Elimination of Carbon Monoxide from the Blood. A Theoretical and Experimental Study. Jour. Clin. Investigation, 1925–1926, *2*, 77.
16. Douglas, C. G., Haldane, J. S., and Haldane, J. B. S.: The Laws of Combination of Haemoglobin with Carbon Monoxide and Oxygen. Jour. Physiol., 1912, *44*, 275.
17. Heller, E., Killiches, W., and Drinker, C. K.: The Evaluation of 5 and 7 Per Cent. Carbon Dioxide Mixtures as Respiratory Stimulants. This Jour., 1929, *11*, 293.

SOME PHYSIOLOGIC REACTIONS TO COOLING POWER DURING WORK, WITH SPECIAL REFERENCE TO EVAPORATION OF WATER*

J. Argyll Campbell and T. C. Angus

From the National Institute for Medical Research, Hampstead, London

Introduction

In a previous paper (1) we investigated some of the body reactions occurring at various temperatures, namely, about 20°, 25°, 30°, and 35°C., in both relatively dry and moisture laden air, still and in motion, using both naked and clothed resting subjects. In the present paper, employing two of the same subjects, we have studied similar body reactions, but in this case the subjects carried out work of moderate intensity and at temperatures of 10°, 15°, 20°, and 25°C. We have, thus, data at air temperatures of 20° and 25°C. both for resting and for working subjects. The physiologic reaction particularly under investigation was the evaporation of water from the skin and lungs; pulse rates, cheek and rectal temperatures, heat production, and heat loss were also considered. This research forms part of the study of Leonard Hill's kata-thermometer as an index of atmospheric conditions suitable for factory and other workers.

Methods

The same experimental tunnel was used as in the previous research (1), to which the reader is referred for details. The plan of investigation was similar, the main difference being that the subjects, instead of sitting quietly, were performing moderate work either pedaling on an ergometer or walking on a conveyor, placed just in front of the balance on which the changes in body weight were measured. In half of the experiments the subjects worked on Schuster's modification of Martin's bicycle ergometer (2), performing about 12,150 kilogrammeters per hour, for six consecutive periods of twenty minutes each; during the first three periods the air was kept almost still, while in the last three periods the large fan was set in motion, the resulting air velocity being about 100 to 130 meters per minute. In this research the subjects faced the wind while at work; in the previous research (1) the subjects sat at rest with their backs to the wind. In the other half of the present experiments the subjects walked on a revolving mat or conveyor similar to that used by Benedict and Murschhauser (3) in their work on horizontal walking; our subjects walked at the rate of 5,400 meters per hour for six periods of twenty minutes each. As with the bicycle ergometer,

*Received for publication July 30, 1929.

half the experiment was performed in still air and half in moving air, air velocity being as stated above and the subject facing the wind. At the beginning and at the end of each period of twenty minutes, the subjects changed their ordinary clothes for a special set of very light clothes—cotton shirt, flannel trousers, thin socks, and light rubber-soled shoes—which had been left hanging in the tunnel overnight, so that all garments worn

TABLE 1.—DETAILS OF ATMOSPHERIC CONDITIONS FROM TWO SERIES OF OBSERVATIONS WITH SUBJECT P.

DATE	AIR MOVEMENT	AIR TEMPERATURE		RELATIVE HUMIDITY	DEW POINT TEMPERATURE	DRY KATA COOLING POWER *millicals. per sq. cm. per sec.*
		Dry Bulb °C.	Wet Bulb °C.	%	°C.	
		Series 1.—Relatively Dry Air				
12/17/28	still	10.4	9.0	84	8.4	9.1
	moving	10.4	9.2	84	8.5	21.7
10/ 1/28	still	15.5	12.6	73	10.3	6.1
	moving	15.2	11.2	61	7.7	17.1
8/ 2/28	still	20.5	16.7	69	14.1	4.7
	moving	20.3	15.7	60	12.1	13.5
8/13/28	still	25.1	18.7	55	14.8	3.2
	moving	25.2	17.5	47	12.7	9.1
		Series 2.—Relatively Moist Air				
1/11/29	still	10.2	9.8	95	9.4	7.7
	moving	10.4	9.8	92	10.2	21.4
10/ 4/28	still	15.9	15.0	90	14.4	6.5
	moving	15.7	15.0	94	15.4	18.5
9/21/28	still	20.0	20.0	100	20.0	5.4
	moving	20.6	20.3	97	20.1	14.6
8/28/28	still	25.2	24.5	94	24.0	3.0
	moving	25.7	24.7	94	24.6	8.7

were weighed on a balance which was accurate to 1 gm.

The subjects were not in the post-absorptive state, as they had partaken of breakfast a couple of hours before the experiment commenced.

In half the experiments the subjects during the experiment were in equilibrium with the air inside the tunnel. The weight of these clothes was only about 1.2 kg.

In the other half of the experiments the subjects, stated, in the tables, to have been naked, wore only a pair of

very light, loose and short knickers, socks, and rubber-soled shoes, the total weight of these being about 0.65 kg., for most of which the shoes were responsible.

After the subjects had worked about an hour, the carbon dioxide output and the oxygen consumption during about ten minutes' work were estimated in some experiments by the method of Douglas and Haldane, and the figures obtained were used for calculation of heat production. The heat produced by the work on the conveyor approximated that produced by the work on the ergometer.

Only one subject was under observation on any one day, the experiment commencing at 10 A.M., and finishing at 1 P.M. Three periods of work of twenty minutes each were performed in still air and then three similar periods in moving air, with only about one or two minutes' rest between the periods. In all, we obtained 128 complete results—64 from each subject. In 32 of these 64 observations the subject walked on the conveyor, while in the other 32 he pedaled on the ergometer. Of these 32 investigations, 16 were carried out with the subjects in the very light clothing, and 16 with the subjects almost naked. In 8 of these 16 observations the air was relatively dry, while in the remaining 8 it was well laden with moisture (Table 1). In 4 of these 8 investigations the air was almost still; in the other 4 it was moving at a velocity of about 100 to 130 meters per minute. Each of these 4 observations was made at a different temperature—10°, 15°, 20°, and 25°C., respectively.

Table 1 gives full details of atmospheric conditions from two full series of observations with subject P. lightly clothed and walking on the conveyor in relatively dry and relatively moist atmospheres. With each subject there were eight such series of observations in relatively dry air and eight in air well laden with moisture. The details of atmospheric conditions for any series resembled very closely the corresponding figures given in Table 1. Broadly speaking, all the experiments were performed at approximately one of the four dry bulb temperatures 10°, 15°, 20°, and 25°C., and these temperatures have been used freely for brevity in description in the tables and text for conditions such as are given in the two series in Table 1.

Physiologic Reactions

Pulse Rates

The pulse rates as counted in the radial artery at the wrist are given in Table 2. The rise in rate which is usually expected under an increase in air temperature was not observed, except when the subjects wore the light clothing and worked in moist still air; here the rates, on the whole, increased as the temperature increased. Probably in all the other series, the conditions for clothing and temperature did not differ sufficiently with regard to degree of heating produced, to bring out the effects of a rise in air temperature; also, the experiments were carried out on different days and there seemed to be some differences due to daily variations which were not easily explained. The pulse rates for all conditions were correlated with the dry kata-thermometer cooling power and the correlation ratio was not high (Table 3).

The average rates for moving air were lower—in most cases appreciably lower—than those for still air; here the cooling effect by wind in reducing pulse rate was obvious.

TABLE 2.—EFFECT OF AIR TEMPERATURE (ETC.) ON PULSE RATE, IN BEATS PER MINUTE

AIR MOVEMENT	AIR TEMPERATURE °C.	DRY AIR								MOIST AIR							
		Naked				Clothed				Naked				Clothed			
		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer	
		P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.
Still	10	95	68	84	88	96	76	93	85	90	74	82	84	93	82	83	78
	15	83	78	89	85	92	84	80	84	90	82	93	84	86	87	86	88
	20	81	78	94	80	89	84	95	85	84	80	89	86	92	84	92	90
	25	81	83	86	86	86	82	94	82	92	84	95	86	104	95	93	90
Av.		85	77	88	85	91	82	90	84	89	80	90	85	94	87	89	87
Moving	10	93	68	84	80	88	80	93	80	83	72	80	77	88	83	79	68
	15	78	76	83	78	86	77	78	78	86	78	87	76	82	77	77	84
	20	81	78	89	70	88	82	94	82	82	76	82	77	86	84	87	90
	25	79	82	91	81	83	79	92	85	86	84	90	81	98	89	96	87
Av.		83	76	87	77	86	80	89	81	84	78	85	78	89	83	85	82

We have some figures for the same subjects under similar conditions at 20° and 25°C., but at rest (1). The pulse rates during work were on an average about 20 beats higher than those while at rest. As might be expected, the greatest differences (23, 26, 25, and 26) were observed in the most heating conditions tested, namely, in moist air when the subjects wore light clothing.

Cheek and Body Temperatures

Cheek temperatures were recorded throughout by rolling the bulb of a delicate thermometer over a small area of skin for about one to two minutes, until constancy was attained. The details which are given in Table 4 indicate roughly a linear relationship between cheek temperature and dry kata-thermometer cooling power; there is a high correlation between these two variables (Table 3). We also carried out some measurements of cheek temperature with a thermojunction

TABLE 3.—TOTAL CORRELATION FOR BOTH SUBJECTS (128 OBSERVATIONS)

	RATIO
Dry kata and cheek temperature °C.	−0.89 ±0.01
Dry kata and loss of body weight	−0.51 ±0.04
Dry kata and water evaporated from skin	−0.50 ±0.05
Dry kata and pulse rate	−0.40 ±0.05

and occasionally found the results to be slightly lower than those with the thermometer. In moist air we found it impracticable to use the thermo-junction.

increase in metabolism of 500 to 600 per cent. due to walking on a treadmill did not appreciably alter the cheek and other skin temperatures.

Wind lowered cheek temperature

TABLE 4.—EFFECT OF AIR TEMPERATURE (ETC.) ON CHEEK TEMPERATURE, IN DEGREES CENTIGRADE

AIR MOVEMENT	AIR TEMPERATURE °C.	DRY AIR								MOIST AIR							
		Naked				Clothed				Naked				Clothed			
		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer	
		P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.
Still	10	30.5	25.9	28.8	27.2	31.7	29.9	31.0	29.2	31.0	22.9	30.9	26.2	33.2	29.2	30.1	27.3
	15	31.9	31.1	31.3	32.1	33.1	32.0	32.6	32.9	32.0	30.6	32.9	31.0	33.2	32.3	33.3	32.3
	20	33.2	33.9	34.4	34.7	34.3	34.0	34.7	34.4	33.5	34.1	34.3	34.0	34.8	34.4	32.5	35.1
	25	34.7	35.4	34.2	35.9	34.6	34.2	35.0	33.7	35.6	35.5	34.9	35.9	35.2	35.1	34.2	35.2
Av.		32.6	31.6	32.2	32.5	33.4	32.5	33.3	32.6	33.0	30.8	33.3	31.8	34.1	32.8	32.5	32.5
Moving	10	25.6	21.1	22.0	22.1	24.6	21.5	22.3	20.4	22.9	21.6	25.3	22.4	24.5	24.0	23.3	21.8
	15	26.6	24.4	27.0	24.5	26.1	26.1	25.7	26.4	26.1	24.0	26.6	23.5	27.1	26.4	25.9	26.4
	20	29.8	29.3	29.4	28.7	29.9	30.3	31.5	29.7	30.1	29.6	30.3	29.1	31.0	32.6	30.5	31.9
	25	31.6	33.3	33.4	34.0	32.1	32.2	33.6	31.3	32.8	33.6	33.8	34.0	34.2	34.3	33.0	33.7
Av.		28.4	27.0	28.0	27.3	28.2	27.5	28.3	27.0	28.0	27.2	29.0	27.3	29.2	29.3	28.2	28.5

Subject R. had usually a lower cheek temperature than subject P.; this may have been due, at least in part, to the fact that R. had a higher evaporation of water from the skin than did P.

We have compared some average results for cheek temperatures under air temperatures of 20° and 25°C. for rest and for work, the results for resting subjects being obtained from our previous paper (1). The cheek temperatures with still air were strictly comparable and, with one exception, showed no constant or appreciable difference due to work; they thus agree with the results given by Benedict and Parmenter (4), who found that an

by from 3° to 5°C. (see averages for still and moving air, Table 4) because it removed the still layer of air next the skin. Another important factor was the air temperature; as this decreased, the cheek temperature also decreased. The kata-thermometer combines these two factors and thus we get the linear relationship between cheek temperature and dry kata-thermometer cooling power, and their high correlation ratio already referred to. Benedict and Parmenter's results give similar indications as to the effects of wind and cold air.

It seems curious that exercise in still air did not markedly increase the cheek temperature. Benedict and

Parmenter suggest that in short spells of exercise this is due to constriction of skin vessels, resulting in a temporary transport of blood from the periphery to the muscles, at least in the initial stages of muscular work. We found that after one hour's work in still air at 20° and 25°C. the cheek temperature was not greatly increased above the resting value; there was, at the same time, an increase in the amount of water evaporated from the skin, and this may have been the factor chiefly responsible.

The body temperature, as measured in the rectum, was obtained in more than half the experiments. At air temperatures of 10° and 15°C. the changes produced by the work were very slight, only about ± 0.2°F.; the same result was observed for most of the experiments at 20°C. There were some few experiments in which the change in rectal temperature was greater than ± 0.5°F.; as might be expected most of these were at the highest temperature tested, namely, 25°C. A curious result with subject R. was a distinct fall of rectal temperature in three experiments; in one case this was obviously due to cooling by wind; in the other two cases the initial temperature was a little high, and increase of blood supply to, and evaporation from, the skin may have lowered it.

Water Evaporated from the Body

The total losses in body weight are shown in Table 5. These include the water evaporated from the skin, water evaporated from the lungs, and also the excess weight of carbon dioxide excreted over oxygen absorbed by the lung. In estimating these total losses we have not used the first weighing, that is, after the first twenty minutes of work; therefore the subject had time to settle down to the new conditions. We carried out some control experiments in which the conditions were kept constant over six periods of work of twenty minutes each and we found that after the first twenty minutes the losses in weight became reasonably constant. We therefore used the average values for the second and third periods of twenty minutes each; as stated already, the subject worked for three such periods in still air, followed immediately by three periods in moving air. Sometimes we reversed the order, that is, the part of the experiment in moving air was performed first, but no great difference was produced thereby in the results for loss in body weight.

The losses in body weight during work on the conveyor were often similar to those during work on the ergometer; the calorific values of the two types of work were similar.

Taking all the observations together, we found that they did not show a high correlation ratio with the dry kata-thermometer cooling power. Above a dry kata cooling power of 14 millicalories per square centimeter per second, the total loss in weight reached a minimum. Under these cold conditions the loss in weight was due almost entirely to water and carbon dioxide coming from the lungs.

From Table 5 it will be observed that with subject P. there were no great differences between the losses in body weight during work at temperatures of 10°, 15°, and 20°C., but at 25°C. there was a definite increase in loss of weight. On the other hand,

subject R. often showed a marked increase in loss of weight at 20°C. as well as at 25°C. These great increases in loss of weight were obviously due to increased evaporation of water from the skin.

between still and moving air with regard to the foregoing metabolic factors. Also the calorific value of the work done on the ergometer agreed fairly closely with that of the work done on the conveyor, the average

TABLE 5.—EFFECT OF AIR TEMPERATURE (ETC.) ON LOSS OF BODY WEIGHT (*I.E.*, WATER EVAPORATED FROM SKIN AND LUNGS+ (CO_2-O_2)), IN GRAMS PER HOUR

AIR MOVEMENT	AIR TEMPERATURE °C.	DRY AIR								MOIST AIR							
		Naked				Clothed				Naked				Clothed			
		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer	
		P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.
Still	10	65	46	55	48	62	60	55	74	57	61	39	94	60	65	34	34
	15	65	55	52	55	70	78	44	85	66	52	50	65	88	117	62	60
	20	60	79	57	46	75	195	55	153	57	78	39	120	73	112	64	150
	25	73	130	154	81	141	279	153	218	135	166	125	106	261	266	149	154
Av.		66	78	80	58	87	153	77	133	79	89	63	96	121	140	77	100
Moving	10	49	33	45	48	61	68	55	61	37	39	44	47	60	54	34	36
	15	50	55	50	48	60	60	33	58	55	52	21	34	30	79	42	48
	20	48	63	45	48	52	120	28	94	33	47	18	51	60	88	40	72
	25	60	141	75	97	108	175	87	149	52	125	38	73	142	218	141	154
Av.		52	74	54	60	70	106	51	91	44	66	30	51	73	110	64	78

In order to estimate the weight of water evaporated from the skin, it is necessary to determine the water evaporated from the lungs in the expired air and also the carbon dioxide excreted in excess of oxygen absorbed. We therefore estimated the carbon dioxide output, the amount of oxygen absorbed, and the volume of air expired over about ten minutes, both in still and in moving air, in about twenty experiments. This number appeared to be sufficient for the purpose and for the degree of accuracy obtainable with the methods employed. There was no appreciable difference

figure for both subjects being about 250 to 260 calories. On three occasions subject P. had a high value, about 300 calories, the original cause of which remains unexplained; accompanying the increase there was marked increase in the percentage of carbon dioxide and a marked decrease in percentage of oxygen in the expired air. On one occasion subject R. also had a high value, 294 calories, but this was associated with an increase in volume of air breathed and was due possibly to a tendency to blow through the mouthpiece during work.

Taking an average value for carbon

dioxide output minus oxygen intake, we found 13 gm. per hour for both subjects.

Averaging the values for volume of air respired, we obtained 14 liters per minute for subject P., and 17 liters for subject R.; these figures representing more than twice the resting volumes. By means of the same formula employed in the previous paper (1), we obtained the average values for water evaporated from the lungs, assuming that, with the volumes quoted, the expired air is still saturated at 33°C. By subtracting from the total loss in body weight these values for excess of carbon dioxide output over oxygen intake and for water evaporated from the lungs, we obtained the figures given in Table 6, for water evaporated from the skin alone. Because of the method of estimating the water evaporated from the lungs, these figures can only be regarded as approximations.

It is only at the highest temperature, 25°C., that a marked increase in water evaporated from the skin occurs in both subjects, but in many cases for subject R. there is a great increase also at 20°C. On fourteen occasions the water evaporated from the skin appeared to be nil. On eleven of these occasions the air was laden with moisture; therefore the heat conductivity and heat capacity of the air next the skin would be greatly increased, and the skin would thus be cooled down. The clothes, too, would be rendered damp under such conditions, and in this way the skin would be actually wetted.

Rubner's (5) figures for a resting subject are in support of our results; at 20°C. in moist air the evaporation from the skin was only 3.6 gm. per hour for his subject, and at 15°C. no figure is given. On three occasions in our experiments where the evaporation was nil, the air was relatively dry and in motion; it is very difficult to understand how water evaporation from the skin can be reduced to nil under such conditions, unless the chilling by wind was great, but it is obvious that the amount must have been reduced to a very low level, too low to be estimated with any accuracy by the rough method used.

It will be observed also from the averages for still and moving air in Table 6 that, on the whole, wind greatly reduced the amount of water evaporated from the skin. Further, the light clothing usually increased the amount evaporated at 20°C. and 25°C.

Over all temperatures the water evaporated from the skin was lowest in naked subjects exposed to moist moving air. Subject R. had a much higher average evaporation of water than P. over all temperatures for each set of similar conditions. It was difficult to explain this, although R. had a slightly larger surface area; P. had a somewhat finer—less dense—skin than R., but it was not possible to detect any definite differences in skin thickness and subcutaneous fat.

Our average increases in water evaporated from the body during work over the resting values—obtained in a previous research (1)—at air temperatures of 20° and 25°C. agree in general with the few results recorded by Rubner (5). In most cases the increase was marked, the highest difference being 146 gm. for subject R., whose figure for rest was 30; the heat produced during work was, of course,

about three times that produced at rest. The amount of water evaporated during work in still air showed a greater excess over that during rest than was the case in moving air. The differences in still air are approximately twice those for moving air, the skin being responsible for most of these differences. This is further evidence that at air temperatures of 20° and 25°C., movement of air is a great factor in reducing evaporation during work.

TABLE 6.—WATER EVAPORATED FROM SKIN ALONE, IN GRAMS PER HOUR

AIR MOVEMENT	AIR TEMPERATURE °C.	DRY AIR								MOIST AIR							
		Naked				Clothed				Naked				Clothed			
		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer	
		P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.
Still	10	24	5	14	7	21	19	14	33	19	20	1	53	22	24	0	0
	15	27	17	14	17	32	40	6	47	30	16	14	29	52	81	26	24
	20	26	43	23	10	41	159	21	117	27	46	9	88	43	80	34	118
	25	40	96	121	47	108	245	120	184	108	140	98	80	234	240	122	128
Av.		29	40	43	20	51	116	40	95	46	55	31	63	88	106	46	68
Moving	10	8	0	4	7	20	27	14	20	0	0	6	6	22	13	0	0
	15	12	17	12	10	22	23	0	20	19	16	0	0	0	43	6	12
	20	14	32	11	12	18	84	0	58	3	15	0	19	30	56	10	40
	25	27	107	42	63	75	141	54	115	25	99	11	47	115	192	114	128
Av.		15	39	17	23	34	69	17	53	12	33	4	18	42	76	33	45

The part played by evaporation of water in aiding heat loss from the body during work was also studied. R. made use of evaporation to a greater extent than did P. When clothed, in dry and still air at 25°C., R. lost by evaporation over 60 per cent. of the excess heat produced at work. In moving air at 20°C., subject P. did not use evaporation of water from the skin to any extent at all for removal of heat produced by work; all the excess heat was removed by radiation, conduction, and convection. Perhaps P.'s skin was finer in texture, but, as already stated, there was no great difference otherwise with regard to skin or subcutaneous fat. R.'s resting metabolism was about 90 calories per hour; he was 19.5 years of age and about 171 cm. in height, weighed about 64 kg., and had a surface area of 1.75 sq.m. P. was 36 years of age and had a resting metabolism of about 75 calories per hour; his height was about 163 cm., his weight about 56 kg., and his surface area about 1.59 sq. m. The ratio of surface to weight was much the same for both subjects. The greater surface area in subject R. may have been responsible in part for the differences observed in amount of water evaporated. Subject R.

appeared to do the work with greater efficiency than subject P.; P. was shorter in stature, particularly with regard to the legs.

Comfort

There were no great differences between P. and R. as to feelings of comfort, although R. had a higher water evaporation from the skin that did P. At 10° and 15°C. under moving air both subjects were uncomfortably cold not only when almost naked but also when very lightly clothed, and the fan had often to be stopped. Under the conditions specified, as long as the dry kata-thermometer cooling power was between 4 and 14 millicalories per square centimeter per second the subjects were fairly comfortable. Table 7 gives details of the feelings and cooling powers. Comfort is designated by a plus (+) sign, discomfort by a minus (−) sign. The sign plus over minus (±) indicates local discomfort, such as cold hands, or a clammy hot feeling more or less localized, as under the armpits. If very light clothing is worn, there is thus a very wide range of atmospheric conditions over which subjects may be fairly comfortable while performing moderate muscular work. In still air when the subjects were either naked or lightly clothed, the work could be done agreeably at 10°, 15°, and 20°C., although on one or two occasions at 10°C. the hands were cold. A temperature of 25°C. was too hot in still air, but both 20° and 25°C. were fairly comfortable in moving air. Our clothed subjects were very lightly clothed, with shirt open at the neck and sleeves rolled up. Such light clothing is suitable for indoor muscular work, and people clothed for winter out-of-door conditions should not perform muscular work indoors with such heavy clothing. There is a wide range of conditions for comfort during moderate work at ordinary temperatures if one is not overclothed, because of the possible variations in heat loss from the exposed skin by physical means. Using about the same air velocity, 100 feet per minute, Vernon (6) found that in the unclothed or the very lightly clothed body such an air current, as contrasted with still air, caused an extra cooling corresponding to a lowering of the air temperature by 2° to 4°F., while in the warmly clad body it corresponded to a lowering of only 1°.

Vernon and Bedford (7) recommended a cooling power of 7 in winter and 6 in summer for workers doing light and sedentary work. Our subjects performed rather harder work than this and were more lightly clad than the average worker. Perhaps the clothes worn by an average industrial worker under ordinary conditions would weigh about 3 kg. We have therefore made some further observations with subject P. in ordinary clothes—weight 2.8 kg.—working on the ergometer at 20°C.; the water evaporation from the skin was increased by these heavier clothes, which consisted of laboratory overall, cotton shirt, light cotton vest, light woolen knickers, flannel trousers, socks, and shoes. The subject was rather warm in still air with this heavier clothing and the amount of water evaporated was increased from about 20 gm. per hour with the light clothing to 81 gm. with the heavier clothing.

In most researches carried on at the present time for any particular industry, full allowance is made for the air temperature which can be attained during the season of the year and also which will suit the industrial process. For harder workers in rather warmer conditions than those studied by us, Vernon (6) recommends, as measures for relief, first a diminution of air temperature, then a lessening of clothing, and lastly movement of air. He points out, however, that when the body becomes moistened with perspiration it is much more sensitive to air movement; this agrees well enough with our results for water evaporated in still and moving air. In actual practice in industry it is often a very difficult matter to reduce air temperature; more attention should therefore be directed to clothing and to movement of air.

The influence of the severity of the task itself on evaporation of water from the skin was also investigated; a decrease in the kilogrammeters per hour performed on the ergometer from 12,150 to 8,100 greatly reduced the evaporation, *e.g.*, from 120 to 53 gm. per hour in still dry air and from 54 to 6 gm. per hour in moving air with the subject wearing light clothing (1.2 kg.), the air temperature being 25°C.

Unfortunately we are not able to compare cooling power with effective temperature as an index of physiologic reactions studied, because at present there are no effective temperature scales for the degree of work under investigation.

Summary

Pulse rates, cheek and rectal temperatures, evaporation of water from

TABLE 7.—COMFORT (+) AND DISCOMFORT (−): FIGURES REFER TO DRY KATA-THERMOMETER COOLING POWER IN MILLICALORIES PER SQUARE CENTIMETER PER SECOND

AIR MOVEMENT	AIR TEMPERATURE °C.	DRY AIR								MOIST AIR							
		Naked				Clothed				Naked				Clothed			
		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer		Conveyor		Ergometer	
		P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.	P.	R.
Still	10	8.7+	8.7±	8.9±	7.9±	9.1+	8.0+	7.9+	8.7+	8.1±	8.1+	7.6+	7.8+	7.7+	7.7+	7.8+	7.8+
	15	6.8+	6.4+	6.4+	6.2+	6.1+	7.2+	6.8+	6.8+	6.7+	6.1+	6.3+	6.2+	6.5+	7.0+	6.6+	7.3+
	20	5.6+	3.7+	5.0+	3.7+	4.7+	5.6±	5.0+	5.2+	5.5±	4.9+	4.6+	4.5+	5.4+	5.1±	4.5+	4.6±
	25	2.9±	2.9±	3.1−	3.2+	3.2±	2.7±	3.1−	3.1−	3.2±	2.5±	2.9−	2.9±	3.0−	2.8±	3.0−	3.1±
Moving	10	19.9−	23.8−	23.4−	21.7−	21.7±	19.9−	21.7−	22.7−	21.1−	20.1−	22.7−	22.0−	21.4±	21.4−	23.7±	22.2±
	15	18.3−	18.3±	15.4−	15.9−	17.1−	17.3+	17.2±	17.0±	17.1−	17.9±	18.6−	18.3−	18.3+	18.2+	18.7±	17.7+
	20	13.0+	14.2±	13.2+	12.9±	13.5+	13.1+	12.9+	12.3+	14.5+	13.7±	13.1+	14.2+	14.6±	11.6+	11.4+	13.4+
	25	9.7+	8.3+	9.2+	6.9+	9.1+	10.2+	8.8+	9.4+	9.4+	7.9+	8.6+	8.2±	8.4+	8.7±	10.5±	8.5+

Vol. 11
No. 9

skin and lungs, heat production, and heat loss have been studied in two nearly naked and two very lightly clothed subjects working on an ergometer (12,150 kilogrammeters per hour) and walking on a conveyor (5,400 meters per hour), while they were exposed to dry bulb temperatures at about 10°, 15°, 20°, and 25°C., with still and moving air, and with relatively dry and moist atmospheres.

The cooling effect of wind caused a decrease in pulse rate. An increase in pulse rate was observed in the lightly clothed subjects working in moist still air, as the temperature increased from 10° to 25°C. At 20° and 25°C., there was an increase in pulse rate of about 20 beats per minute over the values for resting subjects, the increase being greatest under the warmest conditions studied, *i.e.*, in the lightly clothed subjects working in moist air.

Broadly speaking, cheek temperatures showed a linear relationship with the dry kata-thermometer cooling power, movement of air and air temperature being the chief controlling factors. There was no great difference between cheek temperatures for resting and working subjects in still air at 20° and 25°C., perhaps because the amount of water evaporated from the cheek was increased during work and perhaps also, as Benedict and Parmenter have suggested, the circulation in the skin may have been lessened during work. Rectal temperatures as a rule, but not always, increased slightly, by 0.5 to 1°F., during work at 25°C.

With air temperatures of 20° and 25°C. and the air still, the amount of water evaporated from the skin is, as a rule, much increased by moderate work, as compared with the value for rest; the average increase was, in one case, as much as 146 gm. per hour, the figures for rest and for work being 30 gm. and 176 gm. per hour, respectively; the heat produced during work was three times that produced while at rest. There are variations in the response of different subjects with regard to water evaporation. During work the amount of water evaporated from the skin in air at 10°C. was much the same as that in air at 15°C.; in still air at 20°C., it was usually much increased in one clothed subject, but not in the other; at 25°C., both subjects always showed a marked increase. Removal of clothes during work reduced evaporation from the skin, and so did wind. In moist and moving air at 10°, 15°, and 20°C., the amount from the skin was often nearly nil. At dry kata-thermometer cooling powers above 14 the water evaporation from the skin was reduced to a minimum, practically all the evaporation taking place in the lungs. One subject used evaporation of water for removal of excess heat produced by work to a much greater extent than did the other subject who had a slightly smaller surface area. The amounts of water evaporated from the skin under the work specified varied from nil for the coldest conditions to 240 gm. per hour under the warmest conditions.

Greater use should be made of removal of clothing and movement of air to render conditions comfortable for indoor muscular workers. If this is done, there is a wide range of atmospheric conditions above and below 15°C., under which comfort is attained with moderate work. Many conditions giving dry kata-thermom-

eter cooling powers between 4 and 14 millicalories per square centimeter per second were found to be suitable because of the possible variations in heat loss by physical means from the lightly clothed body. Cooling powers below 4 are too hot, while cooling powers above 14 are too cold for very lightly clothed workers, performing the task specified.

This research was suggested by Dr. Leonard Hill, F.R.S., to whom we have been indebted for encouragement and advice. We are indebted also to the subjects who submitted themselves to the tests, and to Prof. Major Greenwood, F.R.S., for the correlation ratios.

BIBLIOGRAPHY

1. Campbell, J. A., and Angus, T. C.: Physiologic Reactions of Resting Subjects to Cooling Power and Effective Temperature. This Jour., 1928, *10*, 331.
2. Schuster, E. H. J.: A Differential Balance for Use with Martin's Bicycle Ergometer. Jour. Physiol., 1920–1921, *54*, cxli.
3. Benedict, F. G., and Murschhauser, H.: Energy Transformations during Horizontal Walking. Carnegie Institute of Washington Pub. No. 231, 1915.
4. Benedict, F. G., and Parmenter, H. S.: Human Skin Temperature as Affected by Muscular Activity, Exposure to Cold, and Wind Movement. Am. Jour. Physiol., 1928–1929, *87*, 633.
5. Rubner, M.: Lehrbuch der Hygiene. Eighth edition. Leipzig and Vienna, Franz Deuticke, 1907, p. 37.
6. Vernon, H. M.: The Influence of Temperature, Air Velocity, and Clothing on the Rate of Cooling of the Human Body. Med. Res. Council, Special Rep. Series No. 100, p. 59. London, H. M. Stationery Office, 1926.
7. Vernon, H. M., Bedford, T., and Warner, C. G.: The Influence of Cooling Power and of Variability of Air Currents on Sensations of Air Movement. *Ibid.*, p. 31.

BOOK REVIEW

GRUNDZÜGE DER HYGIENE. By Dr. med. et phil. *Max Eugling*, a. o. Professor für Hygiene an der Universität in Wien. Second, enlarged and revised edition. Paper. Pp. xiv, 426 with illustrations, bibliography, and index. Berlin and Vienna: Urban & Schwarzenberg, 1929.

The book is a general treatise in the field of hygiene. It is divided into twenty-three sections, each one of which considers specific problems. The first section contains a short discussion of the chemical composition of air, its impurities (in the form of gases and dusts), moisture, condensation, atmospheric pressure, air velocities, etc.; it includes further a good review of the experimental work which has been done on apparatus for making such measurements. In the second and third sections, climate and the fundamentals of body heat are the subjects considered. Section IV deals with clothing materials and presents a few suggestions relating to the choice and cleansing of clothes. The physical and bacterial properties of soil are discussed in Section VI—a little over ten pages. Sections VII and VIII have to do with the hygiene of water supply and food. The hygiene of lodgings and buildings, including the problems of heating, ventilation, illumination, sewerage, and disinfection, is discussed in Sections IX through XIV. Much the greatest part of the book is devoted to the hygienic aspects of microbiology together with a systematic treatise on disinfection. In contrast, the chapters on social hygiene (hygiene of children, of youth, and of old people; tuberculosis, venereal diseases, alcohol, psychopathology, etc.) are restricted.

The section on industrial hygiene is very short. All consideration of industrial diseases (dust, poisons, infections) and their prevention is crowded into eight pages. Problems of venereal and chronic diseases and chronic poisonings are again presented in the section on race hygiene, while in addition is a short discussion of birth control and war losses. In the last section, the hygienic value of gymnastics and sports is treated. The book contains a large bibliography and 152 illustrations.—*Stephen Went.*